Upper critical magnetic fields in superconductor/ferromagnet hybrids

2009 J. Phys.: Condens. Matter 21 254201

(http://iopscience.iop.org/0953-8984/21/25/254201)

IOP PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **21** (2009) 254201 (3pp) doi:10.1088/0953-8984/21/25/254201

Upper critical magnetic fields in superconductor/ferromagnet hybrids

C Cirillo, S L Prischepa[1] and C Attanasio

Laboratorio Regionale SuperMat, CNR-INFM Salerno, Salerno I-84081, Italy
and
Dipartimento di Fisica 'E R Caianiello', Università degli Studi di Salerno, Baronissi, Salerno I-84081, Italy

E-mail: attanasio@sa.infn.it

Received 14 April 2009
Published 29 May 2009
Online at stacks.iop.org/JPhysCM/21/254201

Abstract
We measured parallel upper critical magnetic fields in Nb/PdNi and Nb/CuNi bilayers and Nb/PdNi/Nb and Nb/CuNi/Nb trilayers. In the bilayers case the measurements reveal a dependence of the reduced two-dimensional–three-dimensional crossover temperature, $t_{cr} = T_{cr}/T_c$, on the different values of the superconductor (S)/ferromagnet (F) interface transparencies. In the case of the trilayers we observe that the reduced crossover temperature as a function of the ferromagnetic layer thickness, d_F, reaches a value equal to one only when the π-phase occurs in these systems. Also in this case the influence of the interface transparency on the observed results is discussed.

1. Introduction

The proximity effect in superconductor (S)/ferromagnet (F) systems is a very active field of research, due both to the rich physics originating from the coexistence of two competing orderings, and to the numerous suggestions for the engineering applications of these heterostructures [1]. In these systems the superconducting order parameter does not simply decay in the ferromagnetic metal, as would happen in a normal one, but also oscillates along the direction perpendicular to the interface. Signatures of this inhomogeneous state are, for example, the nonmonotonic dependence of the transition temperature as a function of the ferromagnetic layer thickness [2], negative critical current and reversed density of states in Josephson [3–5] and tunnel [6] S/F/S π-junctions, respectively.

Our investigation focuses on the behaviour of the upper critical fields in S/F structures paying particular attention to the quality of the boundary between the two deposited materials. The interface transparency, T, is a crucial parameter in the study of artificially layered systems, a high value of T being an essential ingredient for the observation of the characteristic features of the S/F structures. For this reason many papers have recently been devoted to the study of the interface transparency both in normal metal/superconductor (N/S) and F/S hybrids [7–11].

We have studied the S/F coupling in $Nb/Pd_{1-x}Ni_x$ and $Nb/Cu_{1-x}Ni_x$ systems, for different values of the Ni percentage. $Pd_{1-x}Ni_x$ and $Cu_{1-x}Ni_x$ are in fact weak ferromagnets, whose magnetic strength can be varied in the meV range changing the Ni content in the alloy. In this way the coupling between superconductivity and ferromagnetism can be studied in a wider range of thicknesses. The idea is to study the influence of the interface transparency on the temperature dependence of the upper critical magnetic field applied in the parallel configuration, $H_{c2\|}(T)$, in different S/F bilayers and S/F/S trilayers. Moreover we suggest that also critical magnetic field measurements can reveal peculiar features of S/F systems, as for instance, a peculiar dependence of the two-dimensional–three-dimensional (2D–3D) crossover temperature, t_{cr}, as a function of the ferromagnetic layer thickness in the S/F/S trilayers.

2. Fabrication

$Nb/Pd_{0.86}Ni_{0.14}$ and $Nb/Cu_{1-x}Ni_x$ ($x = 0.54, 0.58$) bilayers were grown on Si(100) substrates in a dc triode magnetron sputtering system with a base pressure of the order of 1×10^{-7} mbar. The thickness of both the superconducting and the ferromagnetic layer was $d_S = d_F = 30$ nm [12].

[1] Permanent address: State University of Informatics and RadioElectronics, P Brovka street 6, 220013, Minsk, Belarus.

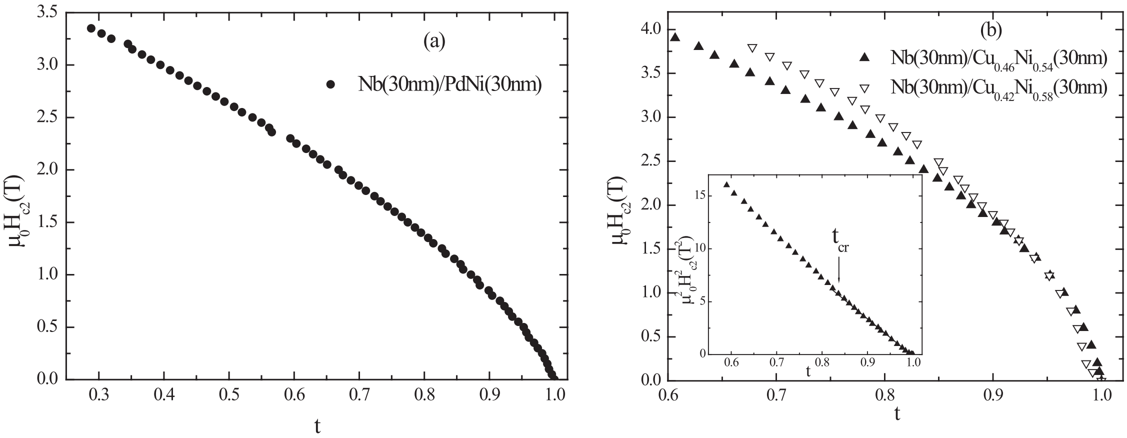

Figure 1. Reduced temperature dependence of the parallel upper critical field of the bilayers (a) $Nb/Pd_{0.86}Ni_{0.14}$, (b) $Nb/Cu_{1-x}Ni_x$ ($x = 0.54$, 0.58). Inset: dependence of the square of $H_{c2\parallel}(T)$. The line, which represents the linear fit to the data, indicates the 2D dependence close to T_c. The arrow shows the reduced crossover temperature, t_{cr}, from the 2D to the 3D behaviour.

The S/F/S trilayers series, namely $Nb/Pd_{0.81}Ni_{0.19}/Nb$ and $Nb/Cu_{0.41}Ni_{0.59}/Nb$, were grown on Si(100) substrates in a UHV dc diode magnetron sputtering system with a base pressure less than 1×10^{-9} mbar. In this case the thickness of the superconducting layer was fixed at $d_S = 14$ nm, while the ferromagnetic film thickness was allowed to vary in the range $d_F = 1-15$ nm. In both cases the rates were controlled by quartz crystal monitors calibrated with low-angle x-ray reflectivity measurements, while the Ni content of the alloys was checked by energy dispersive spectrometry. Critical temperatures and upper critical magnetic fields were resistively measured. Transport properties were studied in a ^{4}He cryostat with a standard dc four probe technique. The magnetic field was supplied by a NbTi solenoid, and applied parallel to the film surface. A detailed investigation of the magnetic and transport properties of the ferromagnetic alloys is reported elsewhere [13].

3. Results

3.1. S/F bilayers

To investigate the role of the interface transparency on the upper critical fields in S/F structures, we first focused on Nb/PdNi and Nb/CuNi bilayers. These samples having only one interface are more controllable systems from an experimental point of view. They can be compared to a single superconducting film having a smaller effective thickness, d_{eff}. At the interface, in fact, superconductivity is destroyed due to the proximity effect. For this reason, the higher the transparency of the barrier, the thinner is d_{eff}. Consequently the 2D–3D crossover from a square-root to a linear dependence, expected for a single Nb thin film [14], moves to lower temperatures when the transparency increases. At $T \approx T_c$ when the superconducting coherence length in the perpendicular direction exceeds d_{eff}, $\mu_0 H_{c2\parallel}(T)$ follows the Tinkham expression:

$$\mu_0 H_{c2\parallel}(T) = \frac{\sqrt{12}\phi_0}{2\pi\xi_\parallel(0)d_{eff}}\sqrt{1 - T/T_c} \quad (1)$$

where $\xi_\parallel(0)$ is the zero temperature value of the Ginzburg–Landau (GL) coherence length parallel to the plane of the layers, and ϕ_0 is the superconducting quantum flux.

The $H_{c2\parallel}(T)$ dependences of the Nb/PdNi and Nb/CuNi bilayers are shown in figures 1(a) and (b), respectively. For all the samples the behaviour of $H_{c2\parallel}(T)$ reveals the conventional 2D–3D crossover reported also for single superconducting films [15]. The signature of the 2D–3D crossover is more evident when plotting $H^2_{c2\parallel}$ as a function of the temperature, as reported in the inset of figure 1(b) for the $Nb/Cu_{0.46}Ni_{0.54}$ bilayer. $H^2_{c2\parallel}$ exhibits two different behaviours: linear for temperatures close to T_c (2D behaviour) and parabolic like at low temperatures (3D behaviour). The reduced crossing temperature between the two regimes, t_{cr}, can be identified as the point where the linear fit, in a quadratic scale, no longer matches the experimental data. We observe a higher crossover reduced temperature in the case of Nb/CuNi bilayers ($t_{cr} \approx 0.83$) with respect to the Nb/PdNi case ($t_{cr} \approx 0.67$) which implies a higher interface transparency of the latter system.

3.2. S/F/S trilayers

Upper critical magnetic fields in the parallel configuration were measured also for S/F/S trilayers. In this case the temperature dependence of $H_{c2\parallel}$ gives important information about the nature and the strength of the coupling between the external S layers. It is well known that for S/N or S/F multilayered structures the temperature dependence of $H_{c2\parallel}(T)$ can show a dimensional crossover. Due to the increase of the perpendicular coherence length, $\xi_\perp$, when the temperature is raised toward the critical temperature T_c, $H_{c2\parallel}(T)$ changes its temperature dependence from a square-root like 2D behaviour at low temperature to a linear bulk 3D behaviour at high temperature [14]. However, the physics of S/F multilayers is more complicated, since at the occurrence of the $0-\pi$ crossover the order parameter spatial distribution suggests that the coupling between the S layers should go to zero (see inset of figure 2). For this reason when the π-phase sets in, namely when the smallest coupling is realized,

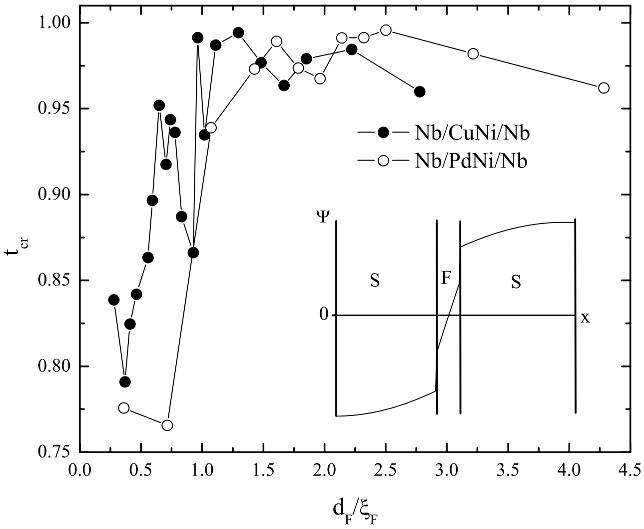

Figure 2. Reduced 2D–3D crossover temperature t_{cr} as a function of d_F/ξ_F for Nb/$Pd_{0.81}Ni_{0.19}$/Nb (open circles) and Nb/$Cu_{0.41}Ni_{0.59}$/Nb (closed circles) trilayers. Inset: sketch of the spatial distribution of the superconducting order parameter, Ψ, in a S/F/S trilayer in the π-state configuration.

we expect a complete 2D behaviour of $H_{c2\parallel}(T)$, resulting in a sudden increase of the reduced crossover temperature.

In figure 2 the reduced crossover temperature for Nb/$Pd_{0.81}Ni_{0.19}$/Nb and Nb/$Cu_{0.41}Ni_{0.59}$/Nb trilayers is presented as a function of d_F normalized with respect to the coherence length in the ferromagnet, ξ_F. In the dirty limit $\xi_F = \sqrt{\hbar D_F/E_{ex}}$ [16] with D_F the diffusion coefficient of the F layer. For $Cu_{0.41}Ni_{0.59}$ we have $E_{ex} = 140$ K and $D_F = 5.3 \times 10^{-4}$ m^{2}s^{-1} [17] while for $Pd_{0.81}Ni_{0.19}$ $E_{ex} = 230$ K and $D_F = 2.3 \times 10^{-4}$ m^2 s^{-1} [18]. This implies that $\xi_{CuNi} = 5.4$ nm and $\xi_{PdNi} = 2.8$ nm. When d_F is of the order of ξ_F, the π-phase sets in [19] and this, as we discussed above, should result in a change of the nature of the coupling between the two Nb outer layers. We can see that t_{cr}, which is related to how strong the coupling between the two outer superconducting layers is, reaches a value equal to one for $d_F \approx \xi_F$. This happens when the π-phase starts to develop and the two Nb layers are more decoupled. In addition, for the Nb/$Pd_{0.81}Ni_{0.19}$/Nb trilayers t_{cr} tends to saturate for higher values of d_F/ξ_F indicating a cleaner interface for this system [8].

4. Conclusions

We measured parallel upper critical magnetic fields in S/F bilayers and S/F/S triple layers. In S/F bilayers we found that the properties of the barrier strongly influence the temperature dependence of $H_{c2\parallel}$. In particular, the temperature at which the 2D–3D crossover takes place moves towards lower temperatures for higher values of the interface transparency. In S/F/S trilayers we observed a complete decoupling of the two external Nb layers only when the π-phase appears in these systems. This happens for higher values of d_F/ξ_F for the Nb/$Pd_{0.81}Ni_{0.19}$/Nb system confirming the higher interface transparency in Nb/PdNi hybrids.

References

[1] Buzdin A I 2005 *Rev. Mod. Phys.* **77** 935
[2] Garifullin I A 2002 *J. Magn. Magn. Mater.* **240** 571
[3] Buzdin A I and Kupriyanov M Y 1991 *JETP Lett.* **53** 321
[4] Ryazanov V V, Oboznov V A, Rusanov A Y, Veretennikov A V, Golubov A A and Aarts J 2001 *Phys. Rev. Lett.* **86** 2427
[5] Kontos T, Aprili M, Lesueur J, Genet F, Stephanidis B and Boursier R 2002 *Phys. Rev. Lett.* **89** 137007
[6] Kontos T, Aprili M, Lesueur J and Grison X 2001 *Phys. Rev. Lett.* **86** 304
[7] Aarts J, Geers J M, Brück E, Golubov A A and Coehoorn R 1997 *Phys. Rev.* B **56** 2779
[8] Fominov Ya V, Chtchelkatchev N M and Golubov A A 2002 *Phys. Rev.* B **66** 14507
[9] Tesauro A, Aurigemma A, Cirillo C, Prischepa S L, Salvato M and Attanasio C 2005 *Supercond. Sci. Technol.* **18** 152
[10] Cirillo C, Prischepa S L, Salvato M, Attanasio C, Hesselberth M and Aarts J 2005 *Phys. Rev.* B **72** 144511
[11] Tagirov L R and García N 2007 *Superlatt. Microstruct.* **41** 152
[12] Angrisani Armenio A, Cirillo C, Iannone G, Prischepa S L and Attanasio C 2007 *Phys. Rev.* B **76** 024515
[13] Iannone G, Zola D, Angrisani Armenio A, Polichetti M and Attanasio C 2007 *Phys. Rev.* B **75** 064409
[14] Jin B Y and Ketterson J B 1989 *Adv. Phys.* **38** 189
[15] Schöck M, Sürgers C and Löhneysen H v 2000 *Eur. Phys. J.* B **14** 1
[16] Ryazanov V V, Oboznov V A, Rusanov Yu A, Veretennikov A V, Golubov A A and Aarts J 2001 *Phys. Rev. Lett.* **86** 2427
[17] Rusanov A 2005 *PhD Thesis* Leiden University
[18] Cirillo C, Rusanov A, Bell C and Aarts J 2007 *Phys. Rev.* B **75** 174510
[19] Shelukhin V, Tsukernik A, Karpovski M, Blum Y, Efetov K B, Volkov A F, Champel T, Eschrig M, Lofwander T, Schon G and Palevski A 2006 *Phys. Rev.* B **73** 174506